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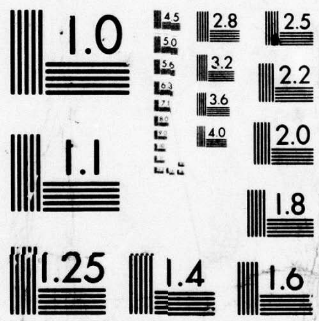
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DETERMINATION OF THE LIGHT ABSORPTION INDEX OF SEAWATER FROM THE LIGHT FIELD PARAMETERS OF AN ISOTROPIC SOURCE

[Pelevin, V. N. and T. M. Prokudina, Opredeleniye velichiny pokazatelya pogloshcheniya sveta morskoy vodoy po parametram svetovogo polya izotropnogo istochnika, in: Optics of the Ocean and Atmosphere (Optika okeana i atmosfery), Institute of Oceanology of the USSR Academy of Sciences, "Nauka" Publishing House, Leningrad, 1972, pp. 148-157; Russian]

A relationship between the light absorption index, κ, of a medium and certain parameters of the state of optical equilibrium, permitting the calculation of κ from measurements of the light field in a homogeneous medium at large depths, was established by A. A. Gershun.[1] This method of determination of κ has also been treated in theoretical and experimental studies by other investigators.[2,3] A generalization of this method to the case of a vertically inhomogeneous plane-parallel medium uniformly illuminated with natural light at the boundary was proposed in Refs. 4 and 5. The latter method is used in applied marine studies conducted by the Institute of Oceanology. It permits the measurement of the vertical distribution of the absorption index $\kappa(z)$ in the sea in daylight from the surface down to depths of 150-200 m. /148*

The method of determination of κ from the parameters of the light field of an artificially directed light source in a scattering medium, proposed in Ref. 6, has been fully substantiated theoretically, but the procedure involved in obtaining the experimental data necessary for calculating κ is very complex. In the simplest case of an axisymmetric light source, it is necessary to move the irradiance meter in the three directions around the selected point in the course of the measurements. In addition, experimental data on spherical irradiance must be obtained.

The irradiance of areas placed along the axis of the light beam is measured with large experimental errors, due to the technical difficulty of providing for a satisfactory cosine characteristic of the irradiance meter in the region of angles close to $\pi/2$. For this reason, it is our view that the latter method is not sufficiently reliable and promising for the determination of κ *in situ* in the sea, where the above-mentioned measurements are particularly difficult to perform. The organization of systematic measurements of absorption index κ in the sea at night and at large depths in the daytime remains a very pressing problem. /149

The present study substantiates the method of determination of κ from the parameters of the light field of an isotropic source in a homogeneous medium. The instruments and method of processing of the experimental data are described. Results of determination of κ are given for several regions of the World Ocean.

Let an isotropic light source be placed in a homogeneous light-scattering and absorbing medium. The boundaries of the medium are sufficiently distant from each other. It is well known that the spatial emission (absorption) density of luminous energy at some point of the light field is equal to the divergence of the vector $\vec{H}$.[1]

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*Numbers in the right margin indicate pagination in the original text.

In the case of an absorbing medium, this relation is

$$\mathrm{div}\,\vec{H} = -\kappa h, \tag{1}$$

where $h = \int_{4\pi} B d\omega$ is the spatial irradiance. Integrating expression (1) over a closed volume located between spheres with radii r and r + dr (with the center of the spheres coinciding with the light source) and using Gauss' theorem, we obtain the equality

$$\int_S \vec{H}(r)\,d\vec{S} = -\varkappa \int_V h(r)\,dV, \tag{2}$$

where S is the sum of the surfaces of the two spheres, and V is the volume included between them.

Considering that as a result of the homogeneity of the medium and isotropy of the light source, the vector $\vec{H}$ is parallel to $d\vec{S}$, and that its modulus H is constant over the entire sphere, we rewrite Eq. (2) as follows:

$$-4\pi r^2 H(r) + 4\pi (r+dr)^2 [H(r) + dH] = -4\pi r^2 dr \varkappa h(r). \tag{3}$$

Removing the parentheses, discarding second-order terms and dividing Eq. (3) by $4\pi r^2 dr$, we obtain

$$\frac{dH}{dr} + H\frac{2}{r} = -\varkappa h.$$

Introducing the notation $\alpha_H = -\frac{1}{H}\frac{dH}{dr}$, we arrive at an expression for κ: /150

$$\varkappa = \left[\alpha_H(r) - \frac{2}{r}\right]\frac{H(r)}{h(r)}. \tag{4}$$

The transport vector modulus H may be expressed in terms of the irradiance of areas oriented in the directions toward the source E and away from the source E':

$$H = E - E'.$$

It should be noted that N. G. Boldyrev once proposed a similar formula for determining κ in the light field of an isotropic source

$$\varkappa = -\frac{dE}{E\,dr} - \frac{2}{r}. \tag{5}$$

A more rigorous conclusion leads to formula (4). It is easy to show that the coefficient $\alpha_H(r) - \frac{2}{r}$ in equality (4) may be expressed in terms of the attenuation index $\alpha_\Phi(r)$ of the flux $\Phi(r)$ through a sphere of radius r surrounding the isotropic source. By definition

$$\Phi(r) = 4\pi r^2 H(r),$$

whence

$$\frac{d\Phi}{dr} = 4\pi\left[2rH(r) + r^2\frac{dH(r)}{dr}\right] = 4\pi r^2\left[\frac{2}{r} - \alpha_H(r)\right]H(r). \tag{6}$$

Denoting

$$\alpha_\Phi = -\frac{1}{\Phi(r)}\frac{d\Phi(r)}{dr} = \alpha_H(r) - \frac{2}{r}. \tag{7}$$

we obtain

$$\varkappa = \alpha_{\Phi}(r)\frac{H(r)}{h(r)} = \alpha_{\Phi}(r)\frac{E(r)-E'(r)}{h(r)}. \tag{8}$$

The coefficient

$$\frac{E(r)-E'(r)}{h(r)} = \bar{\gamma}(r)$$

is the "mean cosine" of the luminance solid at a given point of the light field. Thus, the absorption index of the medium may be calculated from data on the distribution of the light field luminance of an isotropic source. When $r \to \infty$, formula (8) becomes the known relation for the state of optical equilibrium[1] /151

$$\varkappa = \bar{\alpha}\frac{E-E'}{h}, \tag{9}$$

where α is the "deep" light attenuation index.

The light field characteristics of an isotropic source in the sea were measured from the ships AKADEMIK VAVILOV and DMITRIY MENDELEYEV. An outboard photometric bench designed by A. S. Suslyayev was used. The measuring procedure consisted in the following.

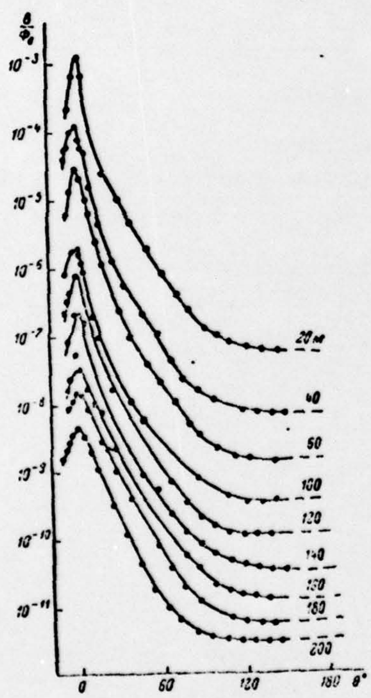

Fig. 1. Distribution of luminance B(θ) in the light field of an isotropic source at various distances r.
St. 347, southern part of the Sargasso Sea, Φ_0 - power of the source.

An isotropic light source (with a quasi-spherical light intensity indicatrix), made from an experimental xenon flash lamp, was placed on the upper carriage of the bench at a depth of 30 m. The photoelectric detector, a luminance meter with a viewing angle of 1 or 10°, made from an FEU-30 PM and covered with a ZhS16+S3S22 glass light filter, was placed on the lower movable carriage. The spectral band of the detector was 495±35 nm. The hinged system of the bench made it possible to scan

with the detector in the plane passing through the source, within ±150° of the direction toward this source. Measurements of the luminance solids were made at distances of 10 to 200 m between the source and the detector. The received signal was fed to /1 an oscillograph screen; the working range of the detector was adjusted by remotely changing: (a) the supply voltage of the PM; (b) the load resistance; (c) the diaphragm in front of the photocathode, specifying the angle or reception of the brightness meter. The measurements were made in the Black Sea and in various water areas of the Atlantic and Pacific Oceans. The vertical homogeneity of the water was checked with an FPR /15 submersible transparency meter.

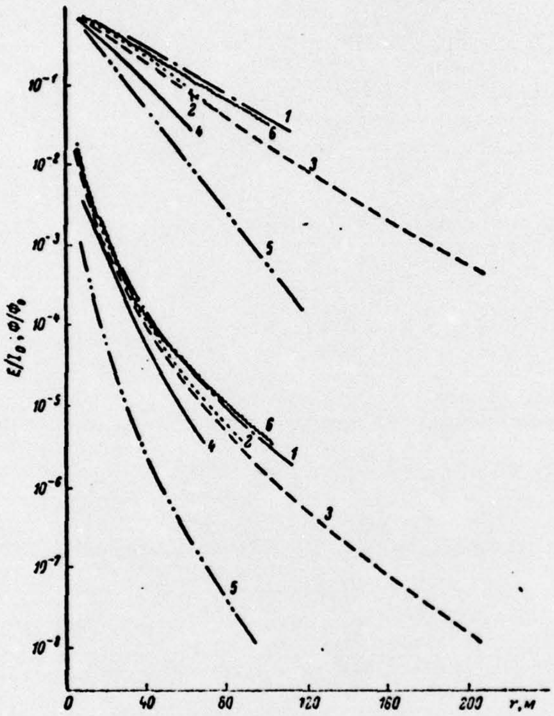

Fig. 2. Irradiance $\frac{E(r)}{I_0}$ and flux $\frac{\Phi(r)}{\Phi_0}$ through a sphere of radius r vs distance r from isotropic source.
Stations: 1 - 397, 2 - 367, 3 - 347, 4 - 342, 5 - 100, 6 - 410; $\Phi_0 = 4\pi J_0$ - power of source.

As an example, Figure 1 shows the results of measurement of the distribution of luminance $B(\theta,r)$ in the light field of an isotropic source in the Sargasso Sea.

Figure 2 shows values of irradiance $E(r)$ and flux $\Phi(r)$ through a sphere of radius r, calculated from measurements of luminance $B(\theta,r)$.

The table gives values of κ calculated from formula (8), and also, for comparison, the results of measurements using the light field of daylight,[4] made on water samples with a "Volna" laboratory differential photometer, and using the signal of laser pulse backscattering (data of D. M. Bravo-Zhivotovskiy et al., obtained during the fifth cruise of the ship DMITRIY MENDELEYEV). The last column of the table gives values of the mean cosine $\overline{\eta}$, used in calculations of κ from formula (8). Good general agreement between the results of measurements using different methods is apparent. A certain

Region of measurements	Absorption index κ, m^{-1} (values given with decimal base)				
	Laboratory photometer. Averaging over spectrum of 490-510 nm and in the 50-200 m depth range.	From backscattering	From light field of solar radiation[4,5]	From light field of isotropic source	Mean cosine $\bar{\eta}$
Sargasso Sea	0.017	0.019	0.018	0.016±0.001	0.88
Central region of Atlantic Ocean (st. 342)	-	-	-	0.023±0.0015	0.88
North tradewind current in the Pacific Ocean (st. 367)	0.016	0.019	0.014	0.016±0.001	0.87
Region of high transparency near Kuka Islands (st. 397)	0.016	0.016	0.012	0.014±0.001	0.89
Pacific Ocean, region southeast of Japan (st. 410)	-	0.013	0.015	0.015±0.001	0.88
Black Sea (st. 100)	-	-	-	0.03±0.002	0.90

discrepancy of the data may be due not only to instrumental errors, but also to different conditions of measurement: about half a day elapsed between the nocturnal and diurnal measurements, and the ship could have drifted into waters with somewhat different characteristics. Measurements of the absorption index from the backscattering signal give the average value of κ in the water layer from the surface down to 30-40 /15 m, whereas the light field of the isotropic source is measured in the depth range from 30 m and below. During the experiment, certain changes are possible in the optical properties of the sample in comparison with the *in situ* state - "spoilage of the sample" - etc. Thus, the results of the comparison of κ values obtained by the proposed method with the data of other measurements should in our view be considered satisfactory.

Since working formula (8) was derived with the only assumption that the medium is homogeneous, the error in the determination of κ (averaged over the depth) is due solely to the experimental error of the measurements of luminance $B(\theta)$, which were used as the basis of the calculation of the absorption index, and to errors of the numerical integration. H, h, and $\bar{\eta}$ were calculated with a "Minsk-22" computer, so that the integration step chosen was sufficiently small, and the calculation error turned out to be much smaller than the measuring error.

Obviously, the maximum possible relative error of the measurement of $B(\theta)$ is

$$\frac{\Delta B}{B} = \frac{1}{B}\left(\Delta B + \frac{\partial B}{\partial \theta}\Delta\theta\right),$$

where ΔB and $\Delta\theta$ are the absolute errors of measurement of luminance and of the angle to which this luminance is attributed.

The value of $\frac{\Delta B}{B}$ is determined by the operational stability of the source and by the calibration accuracy of the receiver, and in our case amounts to 5%. The accuracy of adjustment of angle $\Delta\theta$ is characterized by the certificate for the rotating devices of the outboard bench: $\Delta\theta = \pm 1°$.

Using the data of Fig. 1 for determining the value of the derivative $\frac{\partial B}{B \partial \theta}$, we see that the limiting relative error of the luminance measurement $\frac{\delta B}{B}$ may be estimated at 18% in the range $0° \leqslant \theta \leqslant 10°$; 12% for $10° < \theta \leqslant 20°$; 9% for $20° < \theta \leqslant 30°$; 7% for $30° < \theta \leqslant 60°$; 6% for $60° < \theta \leqslant 180°$. On the basis of these estimates, and considering the contribution of the corresponding sections of θ to the value of H, we obtain a limiting error $\frac{\Delta H}{H}$ not in excess of 10%. The limiting error for α_Φ was estimated from the following formula, obtained from the expression for the total differential α_Φ:

$$\frac{\Delta \alpha_\Phi}{\alpha_\Phi} = \frac{2}{\alpha_\Phi (r_2 - r_1)} \left(\frac{\Delta H}{H} + \frac{\Delta r}{r_1} + \frac{\Delta r}{r_2} + \alpha_\Phi \Delta r \right), \qquad (10)$$

where r_1 and r_2 are the distances between which the mean attenuation index of flux /155
Φ is determined; Δr is the error in the distance measurements.

Substituting into expression (10) the mean values corresponding to our measurements in the Black Sea: $r_1 = 50$ m; $r_2 = 150$ m; $\alpha_\Phi = 0.34\ \mathrm{m}^{-1}$; $\Delta r = 0.25$ m, we obtain a relative error of determination of α_Φ not in excess of 7%. For measurements in the Sargasso Sea, $r_1 = 50$ m; $r_2 = 200$ m; $\alpha_\Phi = 0.016\ \mathrm{m}^{-1}$, and as a result, $\frac{\Delta\alpha_\Phi}{\alpha_\Phi} \cdot 10\% = 9\%$.

We will calculate the limiting error in the determination of the mean cosine of the luminance solid $\bar{\eta}$:

$$\bar{\eta} = \frac{\int_{4\pi} B(\theta) \cos\theta \sin\theta \, d\theta}{\int_{4\pi} B(\theta) \sin\theta \, d\theta} = \frac{H}{h}. \qquad (11)$$

We note that the errors in $B(\theta)$ in the numerator and denominator have the same sign and that in the integration, H and h are calculated as sums of the type $H = \Sigma a_i B_i$; $h = \Sigma b_i B_i$, where a_i and b_i are coefficients dependent only on θ. We thus obtain

$$\frac{\Delta\bar{\eta}}{\eta} = \frac{\Delta H}{H} - \frac{\Delta h}{h} = \sum \frac{a_i B_i}{H} \cdot \frac{\Delta B}{B_i} - \sum \frac{b_i B_i}{h} \times$$
$$\times \frac{\Delta B_i}{B_i} = \sum \frac{\Delta B_i}{B_i} \left(\frac{a_i B_i}{H} - \frac{b_i B_i}{h} \right). \qquad (12)$$

Thus, $\left(\frac{a_i B_i}{H} - \frac{b_i B_i}{h} \right)$ is the weight with which the error in B_i enters into the error of determination of the mean cosine $\bar{\eta}$. Dividing the range of θ into sections, as indicated above, and specifying the corresponding $\frac{\Delta B_i}{B_i}$, one can easily calculate the relative error in the value of the mean cosine (12). We calculated the values

of the expression in parentheses in Eq. (12) from data of specific measurements of luminance solids at distances of 20 and 100 m from the source at station 100 (Black Sea). The corresponding values of $\frac{\Delta\bar{\eta}}{\bar{\eta}} \cdot 100\%$ were found to be 0.65 and 0.8%. The calculation also showed that for other stations as well, $\frac{\Delta\bar{\eta}}{\eta}$ does not exceed 0.8%.

From expression (8), assuming that $\frac{\Delta\alpha_\Phi}{\alpha_\Phi}$ and $\frac{\Delta\eta}{\eta}$ are independent, there follows /156
an expression for the limiting relative error of determination of κ:

$$\frac{\Delta\kappa}{\kappa}=\frac{\Delta\alpha_\Phi}{\alpha_\Phi}+\frac{\Delta\bar{\eta}}{\bar{\eta}}.$$

Considering the above estimates of $\frac{\Delta\alpha_\Phi}{\alpha_\Phi}$ and $\frac{\Delta\bar{\eta}}{\bar{\eta}}$, we obtain $\frac{\Delta\kappa}{\kappa} \leqslant 8\%$ in the Black Sea and $\frac{\Delta\kappa}{\kappa} = \leqslant 10\%$ in the Sargasso Sea. On the whole, we estimate the maximum relative error in the determination of the absorption index at not more than 10%.

Actually, the total error is always an algebraic sum of a large number of particular errors, which can randomly take on both positive and negative values that partly compensate each other. Consequently, it may be expected that the mean statistical error of the result will be much smaller than the limiting value of 10% given here.

CONCLUSIONS

1. A method of determination of the absorption index of light in homogeneous waters from the parameters of the light field of an isotropic radiator has been theoretically substantiated and experimentally verified.

2. *In situ* measurements of the mean absorption index in the 495±35 nm spectral range were carried out in several types of ocean waters. The highest measured value of κ in this spectral range was 0.03±0.003 m^{-1} in waters of the Black Sea; the lowest value was 0.014±0.001 m^{-1} in the high transparency region near the Kuka Islands in the Pacific Ocean.

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